INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR

CROSS REFERENCE TO RELATED APPLICATION

[0001] The present application is a divisional of US Patent Application Serial No. 09/951,282, filed September 13, 2001, which issued as US Patent No. 6,597,079 on July 22, 2003.

BACKGROUND OF THE INVENTION

[0002] This invention relates to an interior permanent magnet synchronous motor wherein a rotor core has a plurality of permanent magnets incorporated or embedded therein and includes magnetic salient pole sections defined between each two adjacent permanent magnets, and more particularly to a permanent magnet-equipped synchronous motor utilizing both reluctance generated due to the salient pole sections of the rotor core and torque by the permanent magnets.

[0003] One of conventional synchronous motors wherein a core between magnetic poles of permanent magnets is provided with magnetic salient pole sections is disclosed in Japanese Patent Application Laid-Open Publication No. 205499/1996. The synchronous motor is constructed in such a manner that rotation of a rotor is limited to only one direction, to thereby displace the silent pole sections, resulting in restraining generation of torque pulsation.

[0004] Also in Japanese Patent Application Laid-Open Publication No. 256455/1996 a technology in which generation of torque pulsation is restrained by changing the width of magnetic poles of magnetic salient pole sections of reluctance

synchronous motor or by displacing a part of pairs of magnetic salient pole sections thereof in a peripheral direction is disclosed.

[0005] Another conventional synchronous motor having permanent magnets incorporated therein is disclosed in Japanese Patent Application Laid-Open Publication No. 18328/1999. The conventional synchronous motor disclosed is so constructed that a width of a core between magnetic poles of permanent magnets is set so as to establish relationship represented by the following expression, to thereby restrain generation of cogging torque:

$$\theta \min \leqq \theta \leqq \theta \max$$

[0006] In the conventional interior permanent magnet synchronous motor, the open angle θ of the rotor core between permanent magnet poles is defined to be within a range of $\theta \min \leqq \theta \leqq \theta \max$ determined depending on the number of teeth, a configuration thereof and a size thereof. However, a timing at which torque is generated between the magnetic poles of the permanent magnets is varied depending on "the number of slots per pole and per phase" q of a stator, so that the synchronous motor fails to satisfactorily restrain cogging torque and torque pulsation.

SUMMARY OF THE INVENTION

[0007] The present invention has been made in view of the foregoing disadvantage of the prior art.

[0008] Accordingly, it is an object of the present invention to provide a permanent magnet-equipped synchronous motor that is capable of sufficiently restraining both cogging torque and torque pulsation during feeding of electricity thereto.

[0009] In accordance with the present invention, a permanent magnet-equipped synchronous motor is provided. The permanent magnet-equipped synchronous

motor includes a stator including a stator core provided with a plurality of magnetic pole sections having windings of at least one phase wound thereon, as well as a rotor having p pole pairs (p: a positive integer of 1 or more). The rotor includes a shaft and a rotor core fixed on the shaft. The rotor core has 2p (a plural number) permanent magnets incorporated therein in a manner to be spaced from each other at intervals in a peripheral direction thereof. The 2p permanent magnets each constitute a permanent magnet magnetic pole section formed on an outer periphery of the rotor core. The rotor is formed with 2p magnetic salient pole sections arranged so as to interpose the permanent magnet magnetic pole section therebetween. It is to be noted that herein "one permanent magnet" means not only one permanent magnet in physical sense, but also such "one permanent magnet" as comprises a plural permanent magnets and yet functions as one permanent magnet magnetically.

[0010] According to the present invention the 2p permanent magnet magnetic pole sections comprise two groups (a first and a second groups) of permanent magnet magnetic pole sections. Each permanent magnet magnetic pole section of the first group is arranged to be spaced at equal intervals in the peripheral direction interposing one permanent magnet magnetic pole section of the second group between each two adjacent permanent magnet magnetic pole sections. Similarly, each permanent magnet magnetic pole section of the second group is also arranged to be spaced at equal intervals in the peripheral direction interposing one permanent magnet magnetic pole section of the first group mentioned above between each two adjacent permanent magnet magnetic pole sections. In other words each permanent magnet magnetic pole section of the two groups is arranged to appear alternately in the peripheral direction.

[0011] Also the 2p (p: a positive integer of one or more) magnetic salient pole sections comprise two groups (a first and a second groups) of magnetic salient pole sections. Each magnetic salient pole section of the first group is arranged to be spaced at equal intervals in the peripheral direction interposing one magnetic salient section of the second group between each two adjacent magnetic salient pole sections. Similarly, each magnetic salient pole section of the second group is also arranged to be spaced at equal intervals in the peripheral direction interposing one magnetic salient pole section of the first group mentioned above between each two adjacent permanent magnet pole sections. In other words magnetic salient pole sections of the two groups are arranged to appear alternately in the peripheral direction of the rotor core. In this instance an open angle of each of the p magnetic salient pole sections of the first group, $\alpha 1$, is set to be smaller than an open angle of each of the p magnetic salient pole sections of the second group, $\alpha 2$. Further the open angles $\alpha 1$ and $\alpha 2$ are set to satisfy the following expression.

$$\alpha 2-\alpha 1 \approx 2\beta-(2n-1)\tau s$$

wherein n is a natural number, β is an angle defined between two salient pole section virtual center lines, CL1 and CL2. τs is a slot pitch of the stator core (denominated in rad). The outer peripheral surface sections of the permanent magnet pole sections of the rotor core may have a contour formed into an arcuate or elliptic configuration.

[0012] When the open angle $\alpha 1$ of the p magnetic salient pole sections of the first group and the open angle $\alpha 2$ of the p magnetic salient pole sections of the second group are defined as mentioned above, torque pulsation can be restrained and torque ripple can be diminished greatly as compared with the case in which the open angle of the 2p magnetic salient pole sections (each magnetic salient pole

section of both first and second group) is set at equal value.

[0013] In this instance the curvature radius R1 of the magnetic pole surface of the p magnetic salient pole sections of the first group is set to be smaller than the curvature radius R2 of the magnetic pole surface of the p magnetic salient pole sections of the second group. Such arrangement permits torque ripple to be diminished as compared with the case in which the curvature radii R1 and R2 are set at the same value. In order to increase torque, on the other hand, the curvature radii R1 and R2 each are preferably set at a larger value than the curvature radii of the end portions of the magnetic pole surfaces of adjacent permanent magnet magnetic pole sections, and yet to satisfy the condition, $R1 < R2$. However, in order to diminish torque ripple further, at the sacrifice of the torque strength, the curvature radii R1 and R2 each may, of course, be set at a smaller value than the curvature radii of the end portions of the magnetic pole surfaces of adjacent permanent magnet magnetic pole sections.

[0014] In this instance the shapes of the 2p permanent magnet magnetic pole sections and the 2p magnetic salient pole sections may preferably be determined so that the contour of the outer peripheral surface sections of the rotor core formed with two adjacent permanent magnet magnetic pole sections and a magnetic salient pole section interposed therebetween may have symmetrical shapes about the salient pole section virtual center lines (CL1, CL2) and yet so that the contour of the outer peripheral surface sections corresponding to the angle of 360°/p about the center of the shaft of the rotor each may be formed into an identical shape, thus resulting in the rotor core having p identical shapes in the outer periphery thereof. Such arrangement prevents electrical voltage unbalance or eccentric force against rotor from being generated because magnetic balance is obtained in the peripheral

direction, even if open angles of magnetic salient pole sections are set at different values.

[0015] When magnetic pole surfaces of permanent magnet magnetic pole sections are formed into arcuate or elliptic shape, each of magnetic pole surfaces of permanent magnet magnetic pole sections of the rotor and each of magnetic pole surfaces of a plurality of magnetic poles of the stator core may preferably be arranged so as to have a gap defined therebetween and having a dimension δ d which satisfies the following expression:

$$\delta \text{ d} = \delta \text{ d0}/\cos[p(\theta \text{ m} - \theta \text{ dm})]$$

wherein δ d0 is the minimum value of the dimension of the gap, θ m is an angle defined from the virtual center line CL3 which extends in the center of the two salient pole section virtual center lines CL1 and CL2 toward the side of the magnetic salient pole section having the open angle α 1. θ dm is an angle between the virtual line PL3 which extends from the center of the shaft through a position where the dimension of the gap has the minimum value and the virtual center line CL3.

[0016] In the above expression, when the value of θ dm is set at 0 (θ dm = 0°), the gap formed will constitute a general gap called "cosec gap". Such a gap configuration permits, irrespective of the direction of the rotation of the motor, a distribution of density of a magnetic flux from the permanent magnets in the gap to approach a sine wave, to thereby restrain cogging torque.

[0017] In this instance, the value of θ dm which permits the value of cogging torque to be minimum is determined by the expression, θ dm≈(ϕ 2- ϕ 1)/2 . Angles ϕ 1 and ϕ 2 will be described in the following. However, when the distribution of density of a magnetic flux from the permanent magnets in the gap deviates greatly from the sine wave, the minimum value of the cogging torque exists within a range of

$(1/6) \times X \times \tau s \leqq \theta dm \leqq (1/2) \times X \times \tau s$

wherein X is a natural number which makes θ dm most approach the value of $(\phi 2-\phi 1)/2$ when the following expression is almost satisfied:

$$\theta dm \approx (\phi 2-\phi 1)/2 \approx (1/4) \times X \times \tau s$$

[0018] In addition to satisfying the above condition, the following expressions should be satisfied also while ϕ 1 is an angle defined between the virtual center line CL3 and the virtual line PL1, which is one of the two virtual lines PL1 and PL2 which extend from the center of the shaft through both ends of each of the magnetic pole sections and yet the virtual line on the side of the magnetic salient pole sections having an open angle α 2, and ϕ 2 is an angle defined between the virtual center line CL3 and the virtual line PL2, which is the other of the two virtual lines PL1 and PL2 and yet the virtual line on the side of the magnetic salient pole sections having an open angle α 1:

$$\phi 2 > \phi 1$$

$$\phi 2-\phi 1 \approx 0.5\,(2m-1)\,\tau s-(180°/p)$$

$$\phi 2+\phi 1 \approx u \cdot \tau s$$

$$\alpha 1+\alpha 2 \leqq (360°/p)-2(\phi 2+\phi 1)$$

wherein m and u are arbitrary natural numbers. When such arrangement as above is satisfied, not only cogging torque can be diminished to the minimum value but also torque ripple can be restrained.

[0019] Moreover in a motor whose size of the gap δ d as mentioned above does not constitute a so-called cosec gap, it is also possible to diminish cogging torque and torque ripple when the relations between the angles ϕ 2 and ϕ 1 and open angles α 1 and α 2 are established as mentioned above.

[0020] Furthermore when α 1, α 2, ϕ 2 and ϕ 1 are set at such values as to

satisfy the following expressions, both cogging torque and torque ripple can be arranged to approach the minimum values.

$$(180°/2p) + (\alpha 1/2) - \phi 2 \approx (1/4)(2v1-1)\ \tau s$$

$$(180°/2p) + (\alpha 2/2) - \phi 1 \approx (1/4)(2v2-1)\ \tau s$$

wherein v1 and v2 are arbitrary natural numbers.

[0021] In order to form a first and a second non-magnetic sections with recesses at both ends in the peripheral direction of the permanent magnets of the rotor core, while the first non-magnetic section is arranged on the side of the magnetic salient pole section having an open angle $\alpha 1$ and the second non-magnetic section is arranged on the side of the magnetic salient pole section having an open angle $\alpha 2$, the shape of the non-magnetic sections may preferably be arranged in such a manner that the area of the cross section of the first and the second non-magnetic sections are the same or the area of the cross section of the second non-magnetic section is larger than the area of the cross section of the first non-magnetic section. Such arrangement permits leakage of magnetic flux from permanent magnets (short circuit of magnetic flux) to be restrained as well as demagnetization to be prevented. However, according to the present invention, the open angle $\alpha 1$ and the open angle $\alpha 2$ have different values, thus the propensity for leakage of magnetic flux from permanent magnets and propensity for demagnetization are different at both ends in the peripheral direction of the permanent magnets. Namely, in case of $\alpha 1 < \alpha 2$, amount of leakage of the magnetic flux from permanent magnets is larger at the end in the peripheral direction on the side of the magnetic salient pole section having the open angle $\alpha 2$ than at the end in the peripheral direction on the side of the magnetic salient pole section having the open angle $\alpha 1$. This leads to more demagnetization of the permanent magnets at the end in the peripheral direction on

the side of the magnetic salient pole section having an open angle of $\alpha 2$ than at the end in the peripheral direction on the side of the magnetic salient pole section having an open angle of $\alpha 1$. From the above view points, the area of the cross section of the second non-magnetic section is arranged to be larger than that of the first non-magnetic section in order to positively restrain the leakage of magnetic flux from permanent magnets from the end portion on the side of the magnetic salient pole section having an open angle of $\alpha 2$ and the demagnetization of the permanent magnets at the end portion thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] These and other objects and many of the attendant advantages of the present invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, in which like reference numerals designate like or corresponding parts throughout; wherein:

[0023] Fig. 1 is a schematic view conceptually showing a first embodiment of an interior permanent magnet synchronous motor or a permanent magnet-equipped synchronous motor according to the present invention;

[0024] Fig. 2 is a schematic view conceptually showing a rotor incorporated in a second embodiment of an interior permanent magnet synchronous motor or a permanent magnet-equipped synchronous motor according to the present invention;

[0025] Fig. 3 is a schematic view conceptually showing a rotor incorporated in a third embodiment of an interior permanent magnet synchronous motor or a permanent magnet-equipped synchronous motor according to the present invention;

[0026] Fig. 4 is a graphical representation showing torque ripple in the

embodiments shown in the Figs. 1-3;

[0027] Fig. 5 is a schematic view conceptually showing a fourth embodiment of an interior permanent magnet synchronous motor or a permanent magnet-equipped synchronous motor according to the present invention;

[0028] Fig. 6 is a graphical representation showing decrease of torque ripple wherein R1 and R2 are varied;

[0029] Fig. 7 is an enlarged schematic view of Fig. 5;

[0030] Fig. 8 is a graphical representation showing relationship between $\phi 2$ and $\phi 1$ which makes the value of cogging torque the minimum in a synchronous motor with eight pole pairs (P=8), 48 slots and distributed windings; and

[0031] Fig. 9 is a graphical representation showing relationship between $\alpha 1$ and $\alpha 2$ that makes the value of torque ripple obtained by the expressions (1), (8) and (9) the minimum.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0032] Now, an interior permanent magnet synchronous motor or a permanent magnet-equipped synchronous motor according to the present invention will be described with reference to the accompanying drawings.

[0033] Referring first to Fig. 1, a stator/rotor structure incorporated in an embodiment of a synchronous motor with built-in permanent magnets or an interior permanent magnet synchronous motor according to the present invention is illustrated. An interior permanent magnet synchronous motor of the illustrated embodiment, as shown in Fig. 1, includes a stator 1, which includes an annular yoke 2 constructed by laminating a plurality of silicon steel plates on each other. The

annular yoke 2 has a plurality of teeth 3 formed on an inner periphery thereof in a manner to be spaced from each other at predetermined intervals in a peripheral direction thereof. The teeth 3 each constitute a magnetic pole section. The teeth 3 are so arranged that each of two adjacent teeth thereof have a slot 4 defined therebetween. The teeth 3 have three-phase windings wound thereon in order, resulting in forming winding sections (not shown). The yoke 2 and teeth 3 cooperate with each other to constitute a stator core.

[0034] In the illustrated embodiment, the stator 1 is so configured that the number of slots Ns is set to be forty-eight (48), the number of pole pairs is four (4), and the number of phases is three (3). Thus, "the number of slots per pole and per phase" q is determined to be $q=48/(2\times4\times3)=2$, and the slot pitch τs is 7.5°.

[0035] The permanent magnet-equipped synchronous motor of the illustrated embodiment also includes a rotor 5. The rotor 5 includes a shaft 6, as well as a rotor core 7 fixed on the shaft 6 and having eight permanent magnets 8 incorporated therein in a manner to be spaced from each other at an interval in a peripheral direction thereof. The rotor 5 includes magnetic silent pole sections 9 and 10 defined between two adjacent permanent magnets 8. The rotor core 7 is formed, on the outer periphery thereof, with a plurality of grooves 11 which extend in both radial direction and axial direction in order to clearly form magnetic salient pole sections 9 and 10. The outer peripheral surface sections of the rotor core 7 defined outside in the radial direction corresponding to the eight permanent magnets constitute eight permanent magnet magnetic pole sections 12.

[0036] The rotor core 7 is likewise constructed by laminating silicon steel plates on each other. Also, the rotor core 7 has through-holes formed at portions thereof at which the permanent magnets 8 are incorporated in the rotor core 7, so that the

permanent magnets 8 may be inserted via the through-holes into the rotor core 7. The permanent magnets in this embodiment are so configured to have a cross section of a rectangular shape respectively.

[0037] In this embodiment the shapes of eight (8) permanent magnet magnetic pole sections 12 and eight (8) magnetic salient pole sections 9 and 10 may preferably be determined so that the contour of the outer peripheral surface sections of the rotor core formed with two adjacent permanent magnet magnetic pole sections and a magnetic salient pole section interposed therebetween may have symmetrical shapes about the salient pole section virtual center lines (CL1, CL2) and yet so that the contour of each of the outer peripheral surface sections corresponding to the angle of 90° about the center of the shaft of the rotor may be formed into an identical shape, thus resulting in the rotor core having four (4) identical shapes in the outer periphery thereof.

[0038] The eight magnetic salient pole sections comprise two groups (a first and a second groups) of magnetic salient pole sections. Each of the four magnetic salient pole sections 9 of the first group is arranged to be spaced at equal intervals in the peripheral direction interposing one magnetic salient pole section of a second group between each two adjacent magnetic salient pole sections 9. Similarly, each of the four magnetic salient pole sections 10 of the second group is also arranged to be spaced at equal intervals in the peripheral direction interposing one magnetic salient pole section of the first group mentioned above between each two adjacent magnetic salient pole sections 10. The open angle $\alpha 1$ of the four (4) magnetic salient pole sections 9 of the first group is smaller than the open angle $\alpha 2$ of the four magnetic salient pole sections 10 of the second group. In this embodiment the slot pitch of the stator core is 7.5° and the slot opening is 2.1°, therefore the open

angle $\alpha 2$ is 15° and the open angle $\alpha 1$ is 7.5°. In this instance the preferable range of the open angle $\alpha 2$ is $12.9° \leqq \alpha 2 \leqq 17.1°$ and the preferable range of the open angle $\alpha 1$ is $5.4° \leqq \alpha 2 \leqq 9.6°$.

[0039] The relation between the open angles $\alpha 1$ and $\alpha 2$ is represented in a general expression as follows and the values of $\alpha 1$ and $\alpha 2$ are determined to satisfy the expression.

$$\alpha 2 - \alpha 1 \approx (2\beta)-(2n-1)\ \tau s \quad \cdots(1)$$

wherein n is a natural number and β is an angle between the two virtual center lines (CL1, CL2) extending from the center of the shaft through the center of two adjacent magnetic salient pole sections. τs is the slot pitch of the above mentioned stator core. In this embodiment n is six (n=6). When the above expression is satisfied, the torque ripple can be greatly reduced as compared with conventional synchronous motors.

[0040] Fig. 2 shows the structure of a rotor incorporated in a second embodiment of the interior permanent magnet synchronous motor according to the present invention. This embodiment differs from the first embodiment on the point that the rotor core is provided with a pair of non-magnetic sections 13 at both sides in the peripheral direction of each of the permanent magnets 8. The open angles $\alpha 1$ and $\alpha 2$ of the respective four magnetic salient pole sections 9 and 10 are determined similarly as in the case of the embodiment shown in Fig. 1.

[0041] The open angle of the grooves 11 can be obtained as the angle ($\beta d - \alpha 1$). In this instance the open angle of the grooves 11 is 1.875°. The angle βd is determined in the following expression:

$$\beta d \approx (1/2)(2n-1)\ \tau s$$

wherein n is a natural number.

[0042] Fig. 3 shows the structure of a rotor incorporated in a third embodiment of the interior permanent magnet synchronous motor according to the present invention. This embodiment differs from the second embodiment on the point that the open angle of the grooves 11 (the dimension of the width of the grooves in the peripheral direction) is larger than the open angle of the grooves 11 in the second embodiment, and the dimension of the length of the permanent magnets 12 in the peripheral direction is shorter than the length of the permanent magnets 12 in the second embodiment. The structure of the rest of the rotor is the same as that of the rotor in the second embodiment. In this embodiment the open angle of the grooves 11 ($\beta f-\alpha 1$) is set at 3.75°. βf is determined in the expression, $\beta f \approx (1/4)(2n-1) \tau s$, wherein n is a natural number also.

[0043] Fig. 4 shows data of the content of torque ripple in the embodiments shown in Figs. 1-3. In the Fig. 4, "A" indicates the value of torque ripple of a conventional interior permanent magnet synchronous motor, wherein each of the open angle of eight magnetic salient pole potions is set at the same value (8.75°). "B", "C" and "D" indicate the content of torque ripple of the interior permanent magnet synchronous motors shown in Figs. 1-3. It is understood in Fig. 4 that with the embodiments of the interior permanent magnet synchronous motor according to the present invention, torque ripple can be reduced greatly.

[0044] Fig. 5 shows the structure of a rotor incorporated in a fourth embodiment of the interior permanent magnet synchronous motor according to the present invention. The structure of the stator core is the same as in the first embodiment of the interior permanent magnet synchronous motor. In Fig. 5, the same reference numerals as in Fig. 1 are used for the similar parts as shown in Fig. 1. In this embodiment eight (2p) permanent magnets 12a, 12b consist of two groups (a first

and a second groups) of permanent magnets, a first group of which consists of four (p) permanent magnets 12a arranged so as to be spaced at equal intervals in the peripheral direction while having one permanent magnet of a second group interposed between each of two adjacent permanent magnets 12a and a second group of which consists of four (p) permanent magnets 12b arranged so as to be spaced at equal intervals in the peripheral direction while having one permanent magnet of the first group interposed between each of two adjacent permanent magnets 12b. Also eight (2p) magnetic salient pole sections 9, 10 consists of two groups (a first and a second groups) of magnetic salient pole sections, a first group of which consists of four (p) magnetic salient pole sections 9 arranged so as to be spaced at equal intervals in the peripheral direction while having one magnetic salient pole section of a second group interposed between each of two adjacent magnetic salient pole sections 9 and a second group of which consists of four (p) magnetic salient pole sections 10 arranged so as to be spaced at equal intervals in the peripheral direction while having one magnetic salient pole section of the first group interposed between each of two adjacent magnetic salient pole sections 10. In this instance the open angle $\alpha 1$ of the four magnetic salient pole sections 9 of the first group is smaller than the open angle $\alpha 2$ of the four magnetic salient pole sections 10 of the second group. In this embodiment also, the open angles $\alpha 1$ and $\alpha 2$ are set to satisfy the above expression (1).

[0045] More specifically, the slot pitch of the stator core is 7.5°; the slot opening is 2.1°. Then the open angle $\alpha 2$ may preferably be set within the range of $12.9° \leqq \alpha 2 \leqq 17.1°$ and the open angles $\alpha 1$ may preferably set in the range of $5.4° \leqq \alpha 1 \leqq 9.6°$. In this instance $\alpha 2$ and $\alpha 1$ are set at 16° and 6.5°, respectively.

[0046] In this instance the shapes of eight (8) permanent magnet magnetic pole

sections 12a, 12b and eight (8) magnetic salient pole sections 9, 10 may preferably be determined so that the contour of the outer peripheral surface sections of the rotor core 7 formed with two adjacent permanent magnet magnetic pole sections 12a, 12b and a magnetic salient pole section interposed therebetween 9 or 10 is configured so as to have symmetrical shapes about the salient pole section virtual center lines CL1 or CL2 and yet so that the contour of the outer peripheral surface sections corresponding to the angle of 90° (360°/p) about the center of the shaft of the rotor each may be formed into an identical shape, thus resulting in the rotor core having four (p) identical shapes in the outer periphery thereof. Such arrangement prevents electrical voltage unbalance at each phase or eccentric force against rotor from being generated because magnetic balance is obtained in the peripheral direction, even if open angles $\alpha 1$ and $\alpha 2$ of magnetic salient pole sections 9, 10 are set at different values.

[0047] In this instance each of magnetic pole surfaces of permanent magnet magnetic pole sections 12a, 12b of the rotor core and each of magnetic pole surfaces of a plurality of magnetic poles of the stator core are arranged so as to have a gap defined therebetween and having a size or dimension δd which satisfies the following expression to constitute a so-called "cosec gap":

$$\delta d = \delta d0/\cos[p(\theta m - \theta dm)] \cdots (2)$$

wherein $\delta d0$ is the minimum value of the dimension of the gap, θm is an angle defined from the virtual center line CL3 which extends in the center of the two salient pole section virtual center lines CL1 and CL2 toward the side of the magnetic salient pole section having an open angle $\alpha 1$. θdm is an angle between the virtual center line CL3 and the virtual line PL3 which extends from the center of the shaft through a position where the dimension of the gap has the minimum value.

[0048] In this instance, the value of θ dm which permits the value of cogging torque to be the minimum is determined by the expression, θ dm $\approx$ (ϕ 2- ϕ 1)/2 . Angles ϕ 1 and ϕ 2 will be described in the following. However, when the distribution of density of a magnetic flux from the permanent magnets in the gap deviates greatly from the sine wave, the minimum value of the cogging torque exists within a range of

$$(1/6) \times X \times \tau s \leqq \theta dm \leqq (1/2) \times X \times \tau s$$

wherein X is a natural number which makes θ dm most approach the value of (ϕ 2- ϕ 1)/2 when the following expression is satisfied:

$$\theta dm \approx (\phi 2 - \phi 1)/2 \approx (1/4) \times X \times \tau s$$

[0049] The shapes of the permanent magnet magnetic pole sections 12a and 12b are formed into arcuate or elliptic configuration so as to make the dimension of the gap δ d approach the value determined in the above expression.

[0050] In this instance the curvature radius R1 of the magnetic salient pole sections 9 having an open angle α 1 is set to be smaller than curvature radius R2 of the magnetic salient pole section 10 having an open angle α 2. When curvature radius R1 of the magnetic pole surface of the p magnetic salient pole sections of the first group is set smaller than curvature radius R2 of the magnetic pole surface of the p magnetic salient pole sections of the second group, the torque ripple can be reduced as compared with the case wherein curvature radius R1 and R2 are set at the same value. In order to increase torque, on the other hand, curvature radii R1 and R2 may preferably be set larger than curvature radii of the end portions of adjacent permanent magnet magnetic pole sections and yet set at such values as to satisfy the condition R1 $<$ R2. Fig. 6 shows the results of the content of torque measured in the conditions of models 1-3, which were arranged in order to recognize

the effects of different conditions on torque. As shown in Fig. 6, the value of torque ripple marked the smallest value in the case of Model 3 wherein the condition $R1 < R2$ was satisfied.

[0051] In the above expression, when the value of θ dm is set at 0 (θ dm = 0°), the gap formed will constitute a general gap called "cosec gap". Such a gap configuration permits, irrespective of the direction of the rotation of the motor, a distribution of density of a magnetic flux from the permanent magnets in the gap to approach a sine wave, to thereby restrain cogging torque. Moreover, when the value of the slot pitch, θ dm, is set within the range between (1/6) slot pitch and (1/2) slot pitch, cogging torque can be reduced greatly while keeping the distribution of density of a magnetic flux from the permanent magnets in the gap in a state of the sine wave. In the embodiment shown in Fig. 5, θ m is set at 2°.

[0052] In addition to satisfying the above condition, the following expressions are satisfied in this embodiment also, while $\phi 1$ is an angle defined between the virtual center line CL3 and the virtual line PL1 which is one of the two virtual lines PL1 and PL2 which extend from the center of the shaft through both ends of each of the magnetic pole sections 12a, 12b and yet the virtual line on the side of the magnetic salient pole section 10 having an open angle $\alpha 2$, and $\phi 2$ is an angle defined between the virtual center line CL3 and the virtual line PL2 which is the other of the two virtual lines PL1 and PL2 which extend from the center of the shaft through both ends of each of the magnetic pole sections and yet the virtual line on the side of the magnetic salient pole section 9 having an open angle $\alpha 1$:

$$\phi 2 > \phi 1 \quad \cdots \quad (3)$$

$$\phi 2 - \phi 1 \approx 0.5\,(2m-1)\,\tau s - (180°/p) \quad \cdots \quad (4)$$

$$\phi 2 + \phi 1 \approx u \cdot \tau s \quad \cdots \quad (5)$$

$$\alpha 1+\alpha 2 \leqq (360°/p)-2(\phi 2+\phi 1) \quad \cdots \quad (6)$$

wherein p is the number of pole pairs and m and u are arbitrary natural numbers. When such arrangement as shown in the above expressions are satisfied, cogging torque can be diminished to the minimum value. More particularly in this instance the angle $\phi 1$ may preferably be set within the range of $11.025° \leqq \phi 1 \leqq 15.225°$. The angle $\phi 2$ may preferably be set within the range of $14.775° \leqq \phi 2 \leqq 18.975°$. At the same time the angles $\phi 1$ and $\phi 2$ are preferably determined so as to satisfy the following conditions:

$1.65° \leqq \phi 2-\phi 1 \leqq 5.85°$; and,

$27.9° \leqq \phi 2+\phi 1 \leqq 32.1°$

[0053] In this embodiment the angle $\phi 1$ is set at 13.125° and $\phi 2$ is set at 16.875°. These values of these angles are obtained, when the following values are put in the above expressions (4) and (5): $\tau s=7.5$ p=4 m=7 u=4

$$\phi 2-\phi 1 \approx 0.5\,(2m-1)\,\tau s-(180°/p) \quad \cdots \quad (4)$$

$$\phi 2+\phi 1 \approx u \cdot \tau s \quad \cdots \quad (5)$$

$\phi 2-\phi 1=0.5\,(2m-1)\,\tau s-(180°/p)=0.5\times(2\times 7-1)\times 7.5-(180/4)$ $=3.75°$

$\phi 2+\phi 1 \approx u \cdot \tau s=4\times 7.5=30°$

[0054] By solving the above two expressions, $\phi 1$ and $\phi 2$ are determined as 13.125° and 16.875°, respectively.

[0055] Based on the values of the above angles $\phi 1$ and $\phi 2$, the optimal values of the θ dm and θ m to make the value of cogging torque the minimum are obtained in the expressions:

$\theta dm=(\phi 2-\phi 1)/2=(16.875-13.125)/2=1.875°$

[0056] Therefore, when θ dm is 1.875($\theta dm=1.875$), the value of cogging torque

becomes the minimum. Then X in the expression $\theta dm \approx (\phi 2 - \phi 1)/2 \approx (1/4) \times X \times \tau s$ is obtained. The value of X to satisfy $(1/4) \times X \times \tau s = 1.875$ is 1.

[0057] Now by substituting 1 for X (X=1) and 7.5 for τs ($\tau s = 7.5$) in the above mentioned expression $(1/6) \times X \times \tau s \leqq \theta dm \leqq (1/2) \times X \times \tau s$, the optimum range of θdm is determined as $1.25° \leqq \theta dm \leqq 3.75°$.

[0058] As shown in Fig. 7, the width in the peripheral direction of the grooves 11a and 11b (open angles) are set at 2.25° and 1.5°, respectively. Also, as shown in Fig. 7 a first and a second non-magnetic sections 13a, 13b formed on the rotor core 7 are configured in different shapes.

[0059] In this embodiment the value of torque ripple can be made the minimum, when $\alpha 1$, $\alpha 2$, $\phi 1$ and $\phi 2$ are determined to satisfy the following expressions (7) and (8).

$$(180°/2P) + (\alpha 1/2) - \phi 2 = (1/4)(2v1-1) \ \tau s \quad \cdots (7)$$

$$(180°/2P) + (\alpha 2/2) - \phi 1 = (1/4)(2v2-1) \ \tau s \quad \cdots (8)$$

wherein v1 and v2 are arbitrary natural numbers.

[0060] In this instance, the angles at different portions are set to satisfy the above expressions of (7) and (8).

[0061] The conditions for the angles at different portions to make the torque ripple the minimum are obtained by solving the simultaneous equations of (3), (4), (5) and (6). Fig. 8 shows the relationship between $\phi 2$, $\phi 1$ and m which make the value of cogging torque the minimum in a synchronous motor with eight pole pairs (P=8), 48 slots and distributed windings.

[0062] The values along the axis of ordinates show the values of $\phi 2$ and the values along the axis of abscissas show the values of $\phi 1$. In Fig. 8, the points shown by small circles are the values which make the torque ripple the minimum

when substituting the determined values of m and u.

[0063] Fig. 9 shows the relationship between $\alpha 1$, $\alpha 2$ and n which are obtained by solving the above expressions (7) and (8). In the embodiments of the present invention, when the values of $\alpha 1$ and $\alpha 2$ are determined to satisfy the relationship shown in Fig. 9, the torque ripple can be reduced to the minimum.

[0064] According to the present invention cogging torque and torque pulsation can be restrained in an interior permanent magnet synchronous motor.

[0065] While preferred embodiments of the invention have been described with a certain degree of particularity with reference to the drawings, obvious modifications and variations are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.